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THE OPTIMIZATION OF A RACE CAR INTAKE SYSTEM

OPTIMIZACIJA SESALNEGA SISTEMA DIRKALNIKA

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Keywords: pressure fluctuation, engine intake design, optimization, air trumpets

Abstract

This paper deals with the optimization of a race car intake system in order to increase engine power output. The goal of optimization was to test how different lengths of intake trumpet influence air mass flow, pressure fluctuations and, consequently, the obtained engine-rated power and torque. Six trumpet lengths were tested using the 1-D AVL BOOST simulation program. The obtained numerical results of engine-rated power and torque were compared with the information obtained from the engine's manufacturer.

The results of optimization indicate that the length of the intake trumpet significantly influences pressure fluctuation in the test engine intake system. At specific trumpet lengths, pressure fluctuation can help to increase air mass flow per engine cycle, which consequently influences engine-rated power and torque. It was found that shorter intake trumpets have an influence on a higher engine-rated power when operating at higher engine rotational speeds. Longer trumpets increase engine-rated torque at lower engine rotational speeds but decrease engine power at higher speeds. For the needs of competition, high peak engine power is desired, so the trumpets with 60 mm length were selected as optimal, because they have the highest peak engine power output at the desired engine speed.

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Povzetek

Predstavljeni članek obravnava optimizacijo sesalnega sistema motorja z namenom izboljšanja njegove moči. Cilj optimizacije je bil raziskati vpliv dolžine vstopnih cevi (tub) sesalnega sistema na masni pretok zraka, tlačna nihanja, moč in navor motorja. V ta namen smo testirali šest dolžin vstopnih cevi z uporabo 1-D numeričnega programa AVL BOOST. Dobljeni rezultati simulacij so bili primerjani s podatki pridobljeni s strani proizvajalca motorja.

Rezultati optimizacije kažejo, da dolžina vstopne cevi pomembno vpliva na tlačna nihanja v sesalnem sistemu testnega motorja. Pri določeni dolžini lahko tlačna nihanja pomagajo izboljšati masni pretok zraka, kar nadaljnjo vpliva na povečanje moči in navora motorja. Iz rezultatov smo spoznali, da krajše dolžine cevi vplivajo na povečanje moči in navora motorja pri višjih vrtljajih. Z uporabo daljših cevi vplivamo na povečanje zmogljivosti motorja pri nižjih vrtljajih in zmanjšanje njegove zmogljivosti pri višjih vrtljajih. Za potrebe tekmovanja potrebujemo večjo moč pri visokih vrtljajih motorja zato smo kot optimalno izbrali cev z dolžino 60 mm.

1 INTRODUCTION

The air intake system of an engine is a major component responsible for delivering the required amounts of air into the engine combustion chamber. In engines with carburetors, intake trumpets can easily be replaced without any other modifications on the engine or its components. Engine component manufacturers offer several types of intake trumpets which differ in their length and diameter. The diameter of trumpet must fit the carburetor diameter used, so the only possible variable is the trumpet length. The length of the intake trumpet influences the airflow inside it, which is highly unsteady. The pressure fluctuation or wave action inside the trumpet consist of resonant acoustic behaviour and the so-called inertial ram effect of air. These were studied experimentally by several authors in the early stages of engine development, [1-3]. Based on experimental results, it was concluded that inertial and acoustic resonance effects could contribute to increases in engine peak performance. The importance of the ram effect and acoustic resonance effect on the volumetric efficiency of the engine is highly influenced by engine speed and intake system characteristics.

In recent years, experimental testing has been replaced using numerical simulations (NS), which are used in several research and engineering fields. Jošt et al., [4], used numerical simulations for improving Kaplan turbine efficiency prediction, Iljaž et al., [5], used NS for the optimization of the SAE formula rear wing while Harih et al., [6-7], used numerical methods in biomechanics. The most commonly used numerical models for analyzing engine intake systems are one-dimensional models, [8]. They can simultaneously take into account the unsteady flow in intake pipes and unsteady air flow through engine valves.

Numerical simulations can be made using commercial or ʻʻin-houseʼʼ codes. Cottyn, [9], used the AVL BOOST simulation program to calculate and study intake the wave dynamics of a single-cylinder Formula 1 (F1) engine. Harrison et al., [10], made a detailed study on the acoustics of the intake system of a single cylinder F1 car. Based on experimental results they derived an acoustic and simple model of the inertia ram effect which allowed them to study both acoustic oscillations and ram effects at different engine speeds. Their conclusions are similar to those made from experimental work in [1-3]. The ram effect has very little or no influence on volumetric efficiency at the lower engine speed of an F1 engine. At higher engine speeds, it can have a strong contribution to the air intake process. At lower engine speeds, acoustic resonance effects have a major influence on the air intake process. Yang et al., [11], used GT-Power software to perform an optimization of the intake system; intake manifold diameters and lengths were used as variables. The results of optimization show that the performance of the 1L four cylinders, naturally aspirated SI engine clearly improves with optimal intake system design.

For many engine intake systems, optimization is focused on engines with specific limitations. Sayyed, [12], and Vichi et al., [13], optimize the intake system geometry of a Formula Student, single-cylinder engine with the goal of increasing engine performance. Several different designs of the Venturi orifice were tested in [12]. The optimal design of selected intake ventured provides the air flow with the lowest pressure drop in the venture orifice. The authors in [13] tested the variable geometry intake plenum designs. The aim of the variable geometry was to provide the optimal intake geometry for different tests of the Formula SAE competition. It was concluded that innovative intake system design could enhance engine performance in specific tests of competition. The optimization of a Formula SAE race car engine was also performed in [14]. The optimization of a four-cylinder, naturally aspirated SI engine was done using 3D CFD code AVL FIRE. The selected optimal intake shape ensures equal loading of the air-fuel mixture to all the cylinders and consequently increases engine power.

In the present paper, the optimal intake system design of a four-cylinder race car engine was determined using the AVL BOOST v2013.2 computational program. The objective of intake optimization was the peak engine power at 5750 engine rotations per minute. The model of the race car engine was made in the program, and the results of engine power and torque from the engine manufacturer were validated. After model validation, several different lengths of engine intake trumpets were tested numerically. The optimal length of intake trumpet provides approximately 7% more engine power in comparison to less optimal trumpet lengths.

2 ENGINE MODEL

The model of the test engine was made in the AVL BOOST computational program. The specifications of the model are presented in Table 1.

Table 1: *Engine specifications*

Engine type	182 AB 1AA 01
Gas exchange	Naturally aspirated
Number of cylinders	4
Bore [mm]	86.4
Stroke [mm]	67.4
Compression ratio	10.15
Total displacement [cm^3]	1584
IVO/IVC (°ATDC)	356/574
EVO/EVC (°ATDC)	144/362

The engine is equipped with two DHLA type Dellorto carburetors with 40mm diameter and 32mm venturi (choke) diameter. The model of the test engine made in the BOOST program is presented in Figure 1.

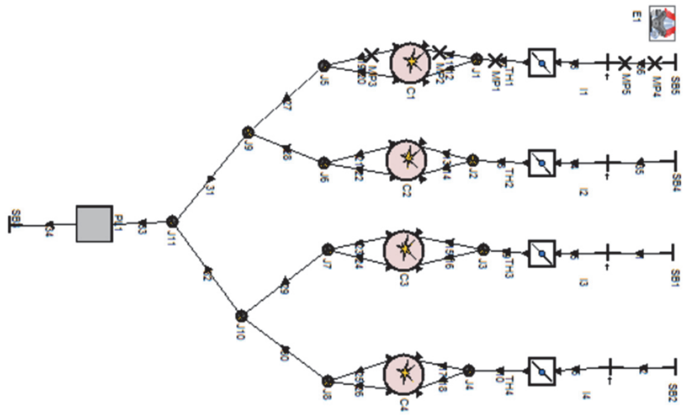

Figure 1: *Engine model in BOOST*

To analyze pressure fluctuation in the intake system, four measurement points were placed in a virtual model of the test engine. The positions of the measurement points is schematically presented in Figure 2.

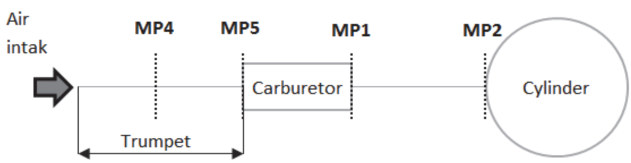

Figure 2: *Schematic of intake system*

Measuring point MP2 was placed in the intake port (before the valve); MP1 was placed after the carburetor. MP4 and MP5 were placed in the centre and the end of the inlet trumpet, respectively.

Air with 25 °C and 1 bar of atmospheric pressure was used as a boundary condition at the intake side. At the exhaust side, a temperature of 250 °C and 1 bar of atmospheric pressure were used. The proper fuel mass flow was regulated with air-fuel equivalence ratio λ, which was set to 1.

3 GOVERNING EQUATIONS

The following governing equation can be written for the engine combustion chamber. The mass conservation equation can be written as:

$$dm = dm_I - dm_E + dm_f - dm_{BB} \tag{3.1}$$

Where m is a mass on air/fuel mixture inside the combustion chamber, m_I is mass of fresh mixture entering combustion chamber, m_E is the mass of exhaust gasses exiting the combustion chamber, m_f is the injected fuel mass, and m_{BB} the mass of mixture blow-by.

The energy conservation equation for the engine combustion chamber can be written using Equation (3.2):

$$dU = dQ - p \cdot dV + dH \tag{3.2}$$

Where dU stands for change of total energy, dQ is the amount of heat transferred to the mixture inside the combustion chamber, p is the pressure, V current combustion chamber volume and dH change of mixture enthalpy. The amount of heat in the combustion chamber transferred to mixture can be divided on heat release during combustion dQ_c and heat losses through the chamber walls dQ_w.

$$dQ = dQ_c - dQ_w \tag{3.3}$$

The total heat released during the combustion process can be calculated using different combustion models. In the presented work, the Vibe combustion model was used for its calculation. Only a brief description of the combustion model used is in the following section. For a detailed description of the model, please refer to [15].

$$\frac{\frac{dQ_c}{Q}}{d\alpha} = \frac{a}{\Delta\alpha_c} \cdot (m+1) \cdot y^m \cdot e^{-a \cdot y^{(m+1)}} \tag{3.4}$$

$$y = \frac{\alpha - \alpha_{id}}{\Delta\alpha_c} \tag{3.5}$$

where Q is total fuel heat input, α is crank angle, a is Vibe parameter and m shape parameter. Vibe and shape parameters were determined based on recommendations of AVL support for specific engine types and operating regimes (engine speeds).

4 RESULTS

The influence of intake trumpet length on a four-cylinder naturally aspirated SI engine was tested numerically. First, the accuracy of the numerical engine model was validated with the results of engine-rated power and torque provided by the engine manufacturer. The engine was equipped with 30-mm trumpets. The results of engine model validation are presented in Figure 3.

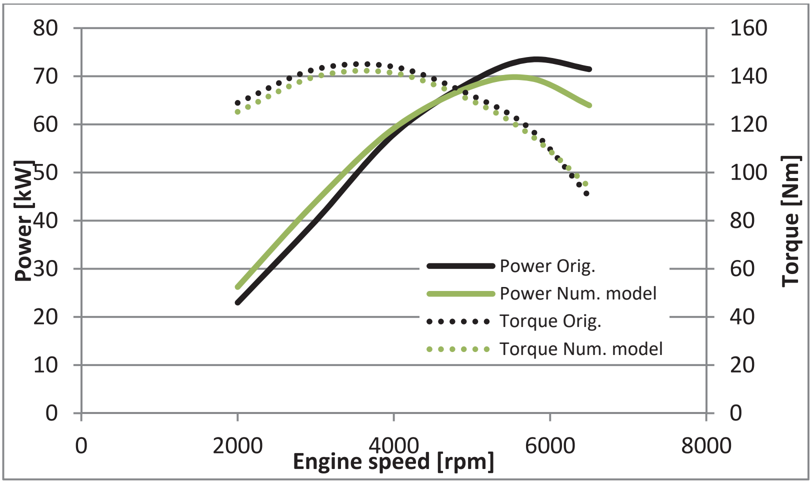

Figure 3: *Results of engine model validation*

The results presented in Figure 3 show good agreement between the numerical model (Power/Torque Num. model) and the original (Power/torque Orig.) results of test engine-rated power and torque. The maximal differenced between engine-rated power and torque are in the range of 10%; average differences are in the range of 5%. This accuracy of test model enables using it for the numerical testing of trumpet length influence on engine characteristics. The following Figure 4-6 presents the numerical results of engine rated-power, torque, and airflow per cycle using different trumpet lengths.

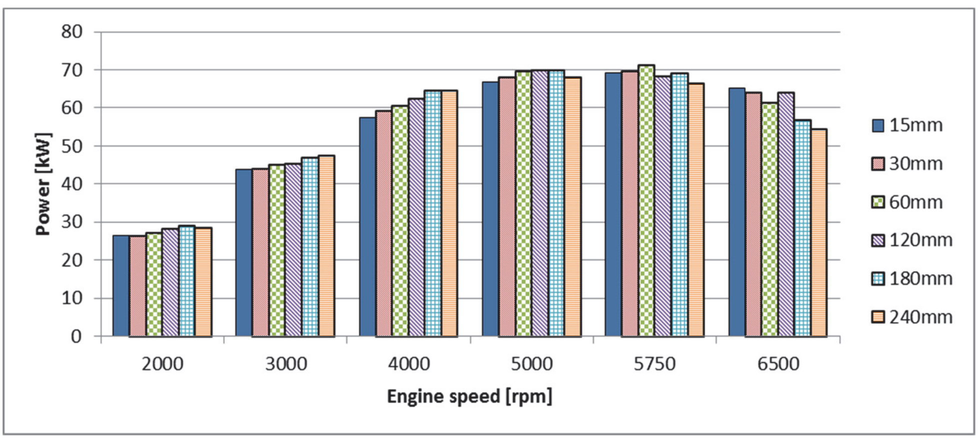

Figure 4: *Numerical results of engine-rated power with different trumpet lengths*

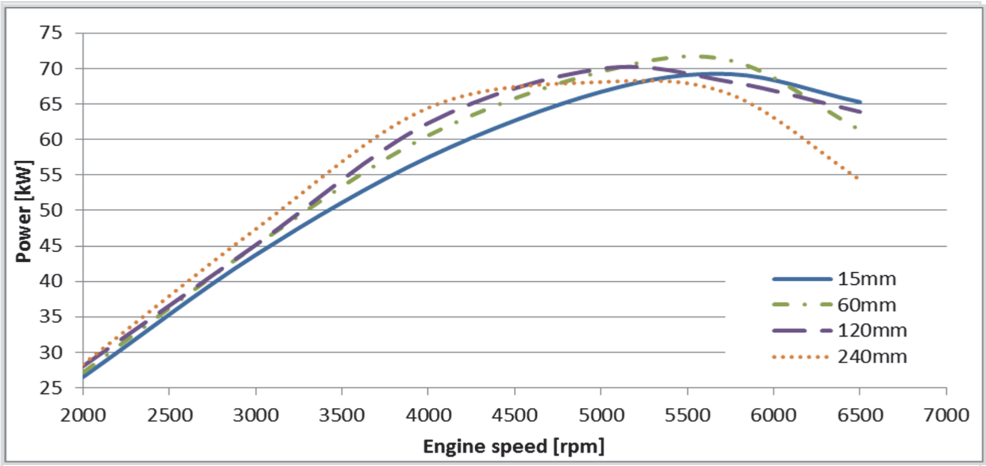

Figure 5: *Numerical results of engine-rated power at selected trumpet lengths*

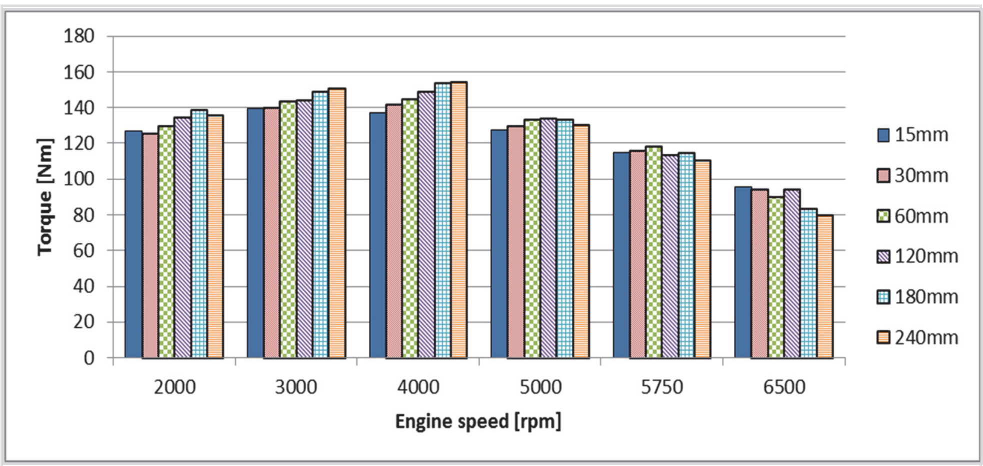

Figure 6: *Numerical results of engine-rated torque with different trumpet lengths*

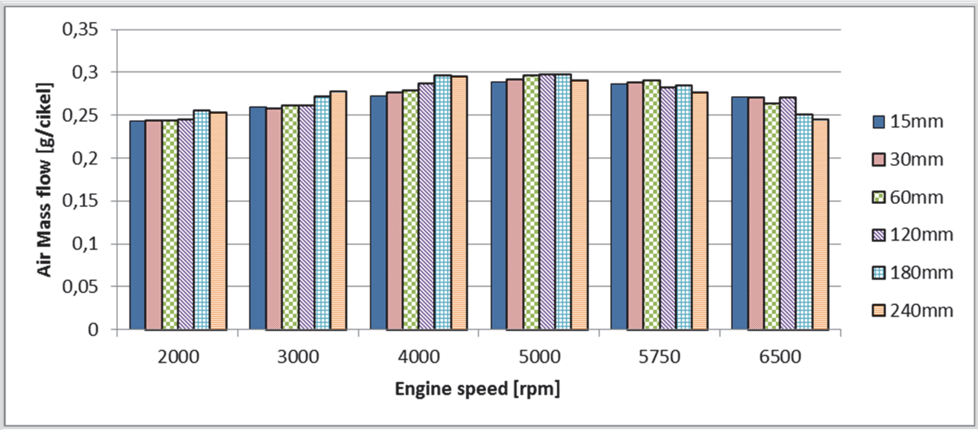

Figure 7: *Numerical results of engine airflow per cycle with different trumpet lengths*

The results of the influence of trumpet length on engine-rated power are presented in Figures 4 and 5. It can be seen that longer trumpet lengths influence higher engine power up to 4000 rpm. At 5000 rpm, almost identical engine power was obtained when using 60-mm, 120-mm, and 180-mm long trumpets. At an engine speed of maximal power (5750 rpm), maximal engine power was obtained using the 60-mm long trumpet. At the highest engine speed (6500 rpm), maximal engine power was obtained with the shortest, 15-mm long trumpet. Maximal power output throughout engine operating range was obtained using 120-mm long trumpets, Figure 5.

The trumpet length also influences the engine-rated torque presented in Figure 6. The longer trumpets increase engine-rated torque at lower engine speeds. At an engine speed of maximal torque (4000 rpm), the maximal engine torque was obtained using 180-mm or 240-mm long trumpets. At 5750 rpm (engine speed of maximal power), the highest torque was obtained using a 60-mm long trumpet. At the highest engine speed, maximal torque was obtained using a 15-mm long trumpet.

The differences in engine-rated power and torque are a consequence of different air mass flows at different trumpet lengths presented in Figure 7. The highest air mass flow at 4000 rpm was obtained using a 180-mm long trumpet, while at 5750 rpm, a 60-mm long trumpet provides maximal air flow per engine cycle. Different lengths of trumpets influence the air pressure fluctuation in the intake system which further influence the air mass flows. Pressure fluctuations in the intake system for 60-mm and 240-mm long trumpets at 4000 and 5750 rpm are presented in Figures 8-11.

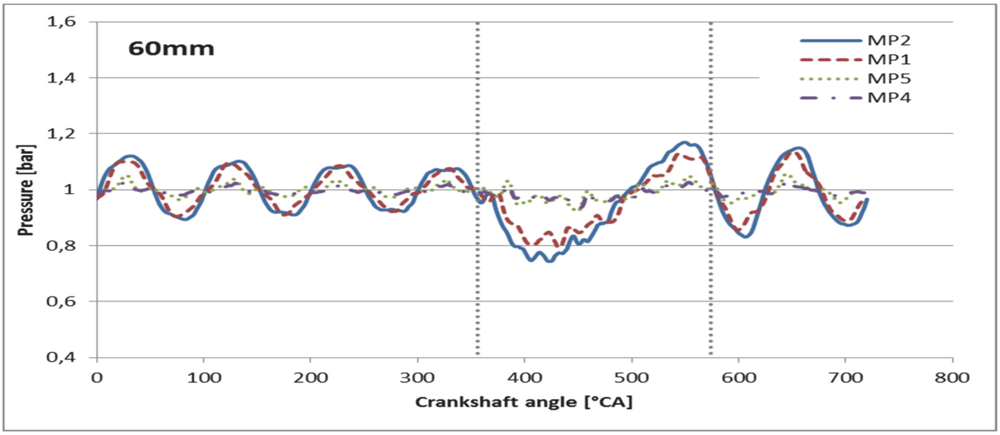

Figure 8: *Pressure fluctuation in MP at 4000 rpm (60-mm trumpet)*

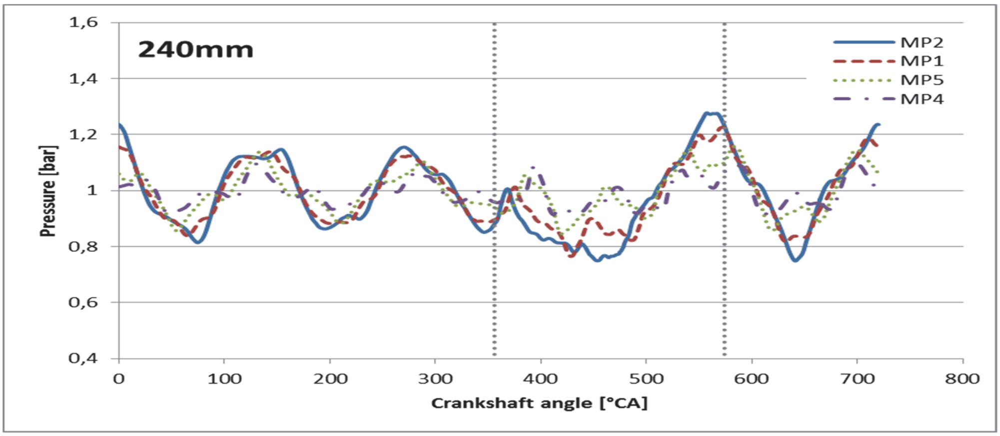

Figure 9: *Pressure fluctuation in MP at 4000 rpm (240-mm trumpet)*

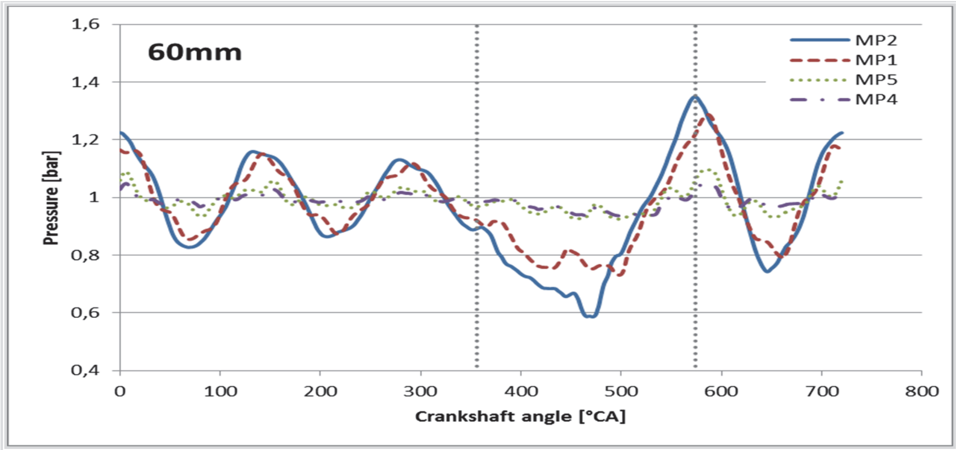

Figure 10: *Pressure fluctuation in MP at 5750 rpm (60-mm trumpet)*

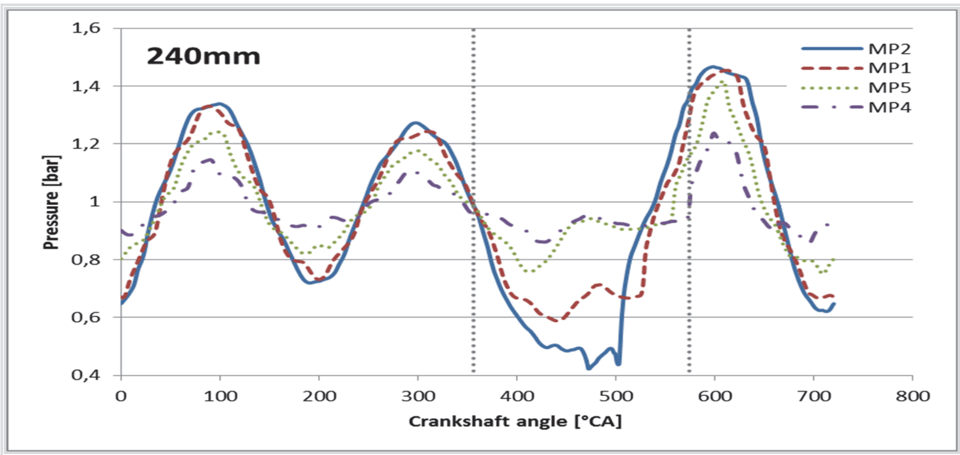

Figure 11: *Pressure fluctuation in MP at 5750 rpm (240-mm trumpet)*

The results of pressure fluctuation in the inlet system are presented in Figures 8-11. Lower amplitude pressure fluctuations with higher frequency before intake valve opening were obtained using a 60-mm long trumpet at 4000 rpm. Higher amplitudes of pressure fluctuation at 5750 rpm were also obtained when using a 240-mm trumpet. At the moment of intake valve opening the pressure inside intake system drops because of the engine air suction. The maximal pressure drop at 4000 rpm is similar for both trumpet lengths and is approximately 0.25 bar below atmospheric pressure. The length of trumpet highly influences the pressure drop at 5750 rpm. At this engine speed, a pressure drop of 0.4 bar was obtained using a 60 mm trumpet. When using a 240-mm trumpet, a 0.6-bar pressure drop was obtained at high engine speed. The intake valve starts to close at 365 degrees and causes the reduction of the cylinder air intake area. At this angle, the pressure inside the air trumpet starts to rise and reaches its maximum value around the intake valve closing angle (574 degrees). The maximum pressure rise inside the trumpet is in a similar range as the maximal pressure drop.

The results of pressure fluctuation presented in Figure 8 to Figure 11 also show how pressure waves spread across the intake system. At lower trumpet lengths, higher pressure oscillations were obtained at MP2 and MP1. At MP5 and MP4, pressure oscillations were lower. When using longer trumpets, higher pressure oscillations were obtained at all measuring points. The difference in pressure oscillations influences average pressure during the air intake process, presented in Figure 12.

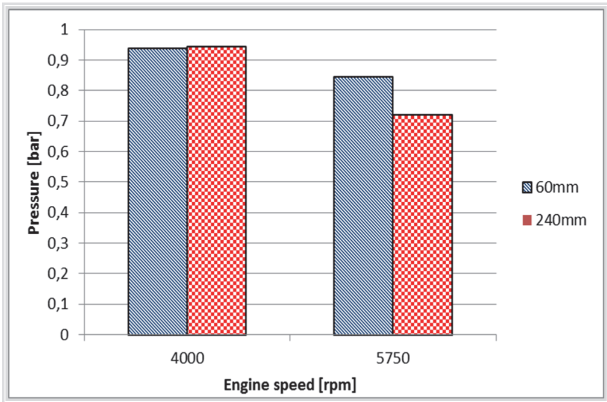

Figure 12: *Average pressure in MP2 during the air intake process*

The results of average pressure inside the intake system at MP2 presented in Figure 12 indicate that at lower engine speed longer trumpet length increases air pressure during engine suction. At higher engine speeds, a shorter intake trumpet provides higher air pressure compared to a 240-mm long trumpet.

5 CONCLUSIONS

The influence of intake trumpet length on race car engine performance was studied numerically. The obtained results indicate that trumpet length influences the pressure fluctuation in the intake system, which further influences air mass flow per engine cycle, engine-rated power and torque.

The results of pressure fluctuations obtained at the measuring point are showing that height of the peak pressure matches the minimum value of pressure in the inlet system. According to Harrison et al. [10], this indicates that only the acoustic oscillations of air are present inside the intake system. There is no indication that shows an inertial ram effect.

At lower engine speed longer trumpets contribute to higher air mass flows and better engine performances. At higher engine speed longer trumpets tend to “choke” air flow and cause a reduction in air mass flow in comparison to shorter trumpets. This causes a reduction in engine-rated power and torque.

A longer trumpet contributed to higher air pressure during the air intake period at 4000 rpm. At 5750 rpm, the higher pressure during the intake period was obtained when using a shorter trumpet.

The optimal design of the intake system depends on desired engine specifications. If the driver wants to have the peak engine power at maximal engine power speed (5750 rpm), the optimal length of intake trumpet is 60 mm. If maximal engine power is to be obtained in the wide range of engine speeds, then 120-mm long trumpets are the optimal solution.

6 ACKNOWLEDGEMENTS

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